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DEVELOPMENT AND TESTING OF A FRICTION-BASED POST-INSTALLABLE SENSOR FOR SUBSEA FIBER-OPTIC MONITORING SYSTEMS

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ABSTRACT

This paper presents the design and development of a friction-based coupling device for a fiber-optic monitoring system that can be deployed on existing subsea structures. This paper provides a summary of the design concept, prototype development, prototype performance testing, and design refinements of the device. The results of the laboratory testing of the first prototype performed at the National Aeronautics and Space Administration (NASA) Johnson Space Center (JSC) are included in this paper. Limitations of the initial design were identified and future design improvements were proposed. These new features will enhance the coupling of the device and improve the monitoring system measurement capabilities.

A major challenge of a post-installed instrumentation monitoring system is to ensure adequate coupling between the instruments and the structure of interest for reliable measurements. Friction-based coupling devices have the potential to overcome coupling limitations caused by marine growth and soil contamination on subsea structures, flowlines or risers. The work described in this paper investigates design of a friction-based coupling device (friction clamp), which is applicable for pipelines and structures that are suspended in the water column and those that are resting on the seabed. The monitoring elements consist of fiber-optic sensors that are bonded to a metal clamshell with a high-friction coating. The friction clamp has a single hinge design to facilitate the operation of the clamp and dual rows of opposing fasteners to distribute the clamping force on the structure. The friction clamp can be installed by divers in shallow depths or by remotely operated vehicles in deep-water applications. NASA-JSC was involved in the selection and testing of the friction coating, and in the design and testing of the prototype clamp device. Four-inch diameter and eight-inch diameter sub-scale friction clamp prototypes were built and tested to evaluate the stain measuring capabilities of the design under different loading scenarios. The testing revealed some limitations of the initial design concept, and subsequent refinements were explored to improve the measurement performance of the system.

This study was part of a collaboration between NASA-JSC and Astro Technology, Inc. within a study called Clear Gulf. The primary objective of the Clear Gulf study is to develop advanced instrumentation technologies that will improve operational safety and reduce the risk of hydrocarbon spillage. NASA provided unique insights, expansive test facilities, and technical expertise to advance these technologies that would benefit the environment, the public, and commercial industries.

INTRODUCTION

In the OMAE2015-41305 paper, “Development and Testing of a Post-Installable Deepwater Monitoring System Using Fiber-Optic Sensors”, the development of an adhesive-based post-installable fiber-optic monitoring system was discussed [1]. An adhesive-based system was developed and successfully employed in an offshore tension leg platform in a shallow water application

[2]. In addition to the adhesive-based system, a friction-based system was also being developed. The friction-based system was intended to be used for both shallow and deep water structural health monitoring applications, where post-deployment installation of the adhesive-based system is not feasible. The friction-based system are designed for installation to subsea structures such as pipeline and offshore tension leg platform support structures. This paper documents the continuing development of the friction-based system. The development process for the friction-based system, friction clamp, is illustrated in Figure 1. Two design iterations, Mark I and Mark II were completed and discussed in this paper.

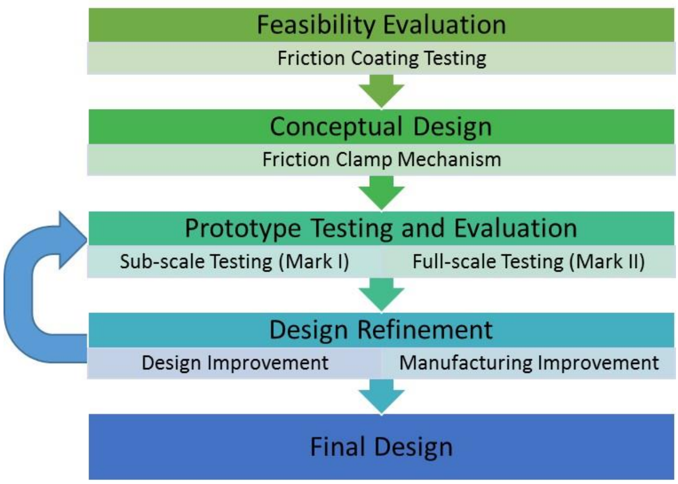

Figure 1. FRICTION-BASED SENSOR CLAMPS DEVELOPMENT PROCESS FLOW CHART

The development initialed by the proposal of the friction-based clamp mechanism design concept and study was conducted to evaluate the feasibility of the concept. The feasibility evaluation focused on evaluating the technical challenge associated with implementing the friction clamp design. After the feasibility evaluation, the first design, Mark I, was formulated. Proof-of-concept testing were conducted to assess the effectiveness of the friction coupling mechanism design and the quality of the measurement signals. The Mark I proof-of-concept testing involved building and testing sub-scale prototypes. 4-inches and 8-inches diameter sub-scale Mark I prototypes were built and installed onto test pipes for testing. They were tested to evaluate their ability in measuring the strain generated by mechanically loading the test pipes in tension, compression, and bending modes. Based on the results and findings from the sub-scale prototype testing, the design was reevaluated and refined. The refinements were incorporated into the Mark II design. The Mark II proof-of-concept testing involved testing 24-inches full-scale prototype. The detail development and testing of the Mark I friction-based system are detailed in this paper. The various challenges and lessons learned during the development of the Mark I design are also presented. The Mark II design improvements and the preliminary findings from the Mark II proof-of-concept testing are also briefly discussed in this paper.

The works described in this paper are the results of a collaboration between National Aeronautics and Space Administration (NASA) Johnson Space Center (JSC) and Astro Technology Incorporated (ATI) [3]. The collaboration was carried out under a Space Act Agreement (SAA) between NASA-JSC and ATI. The SAA allow commercial industries to utilize the unique NASA resources, expertise, and technologies to develop new technologies that can benefit both the U.S. Government Space Program and the commercial industries.

FRICTION CLAMP CONCEPTS

A post-installable fiber-optic based structural health monitoring sensor system concept was proposed by ATI. The fiber-optic sensor system would measure and record temperature, stress, and strain data for offshore subsea applications. The system could provide vital information for operators to monitor the structural integrity of their hardware and enhance their operation and safety. The system can be installed before or after the structure or hardware was deployed. It can be custom tailored for installation onto surfaces of different submerged structures. ATI defined the functions and attributes of the system, and they are outlined below. ATI collaborated with NASA-JSC to jointly develop a friction-based coupling mechanism for the fiber-optic sensor system to provide these functions.

- It can be installed onto structure underwater post-deployment.
- It can be installed by remotely operated vehicle (ROV).
- It can be installed, operated, and survive in deep water and seabed environment.
- It has a robust and reliable coupling mechanism to maintain.
- It provides accurate and reliable sensing and data transmission.
- It is corrosion resistance.
- The installation and operation is insensitive to contaminants from the environments.

FEASIBILITY EVALUATION

Before the first design concept was formulated, a feasibility study was conducted at NASA-JSC to assess the critical technical function of the friction clamp design could be achieved. The objective of the feasibility study is to identify a metal surface treatment that would eliminate slippage between the sensor clamp and the coupling structure. A robust and effective coupling surface that has high friction property is required to maintain a reliable coupling of the friction clamp sensor elements to the structure of interest. A reliable coupling between the clamp and structure are needs for accurate sensing. The treated surface should also be corrosion resistance to the typical offshore deep-sea environments and provide protection to the underlying metal.

Various finishes or coatings for stainless-steel surface of the friction clamp were tested and evaluated. Research on friction joints was conducted, and several metal surface finishes and coatings were selected for testing. They were chosen based on their favorable friction criteria and corrosive resistance properties. The first series of tests evaluated various friction agents and surface finishes. These friction agents were made in NASA-JSC from a combination of abrasive particles and binders. The second series of tests evaluated 4 grades of proprietary commercial-of-the-shelf (COTS) carbide coating.

Friction coating tests were conducted at NASA-JSC. Non-standard shear friction tests were performed to evaluate the shear strength of the treated surface against bare steel surface. The objective of the testing was to compare the shear strength of different treated surfaces. A friction test assembly consists of a bolted metal plate assembly with different treated surfaces. The plate assembly comprised of 2 slotted tension plates clamped together by two joint plates with bolts, washers and nuts. A photograph of the friction test assembly is shown in Figure 2. The joint plate surface was treated with the friction finish or coating, and it represented the clamp side. The metal surface on the tension plate, which represented the structure side, had no surface treatment. The bolts of the assembly were torqued to 30 in-lbs., and the assembly was pull tested with a universal testing machine. Peak shear load occurred at the start of slippage was measured and recorded. A photograph of the shear friction test setup is shown in Figure 3.

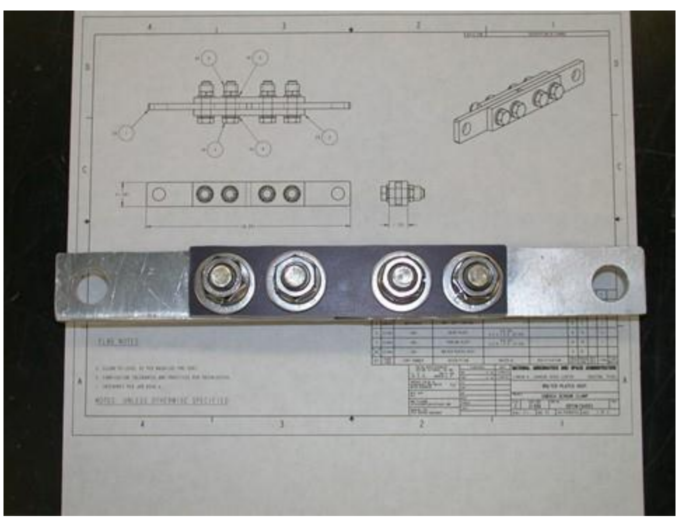

Figure 2. FRICTION TEST ASSEMBLY

The friction agents used in the first series of tests included the following mixture combination of binders and abrasives: Acrylic, epoxy, epoxy primer, aluminum oxide, silicon carbide (FEPA 60 & 100) and boron carbide (FEPA 60 & 100). Under high compressive load from the clamping, the abrasives would embed themselves into the underlying metal of the faying surfaces, thereby creating strong anchors across the two mating pieces. The abrasives, with their high strength and hardness, would bear the brunt of the shear and prevent slippage. The binder served as a medium for application and a layer of corrosion protection.

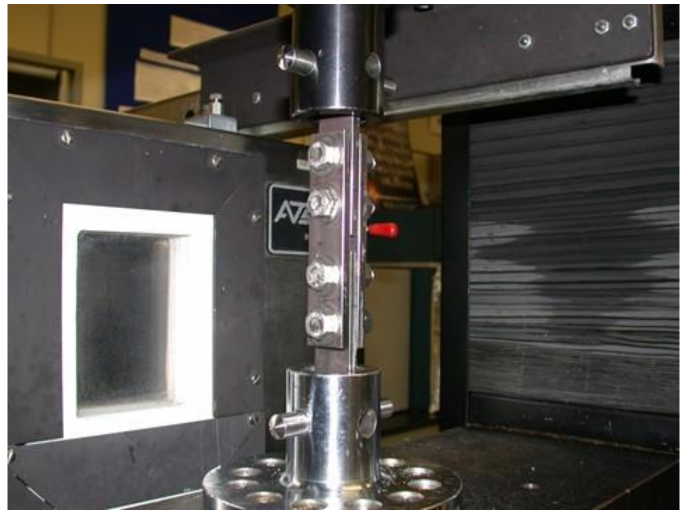

Figure 3. SHEAR STRENGHT TEST SETUP

The shear friction test results of the first series of friction agents are shown in Table. 1. For comparison, tests were also done on a bolted assembly without any surface treatment and with knurling. The results indicated that the bare metal surface without any surface treatment provided the most friction. None of the friction coating or knurled finish evaluated provided any improvement over the bare metal surface. The poor performance of the friction agents could be attributed to the failure of achieving a cohesive and uniform abrasive coating on the metal surface. It was observed that the abrasives were not well dispersed and tended to clump together during application. As a result, the abrasives ended up rubbing against themselves rather than embedding into the faying metal surfaces.

Table 1. FIRST SERIES OF SHEAR FRICTION COATING TEST RESULTS

Surface Treatment	**Peak Load (lbf)**
None, Bare Metal Surface	2496
Knurled (sharp diamond pattern .05 deep)	2057
Mil Spec Standard Epoxy Coating w/ Aluminum Oxide	1738
Epoxy Primer w/ Aluminum Oxide	1315
Black Silicon Carbide 60 w/ Epoxy Primer	1537
Black Silicon Carbide 100 w/ Epoxy Primer	1622
Boron Carbide 60 w/ Epoxy Primer	1247
Boron Carbide 100 w/ Epoxy Primer	1267

For the second series of shear friction tests, four grades of carbide coating were evaluated. The carbide coatings have high resistance to wear and corrosion. The carbide is metallurgically bonded through an electrofusion process. Grades 1 to 3 of the coatings contain tungsten carbide grits. Grade 4 contains stellite grits, which are made of a cobalt-chromium alloy. The build-up thickness of each grade ranges from 0.0025” to of .017”. Joint plates of the test assemblies were sent to the manufacturer to apply the coating.

The test results for the carbide coatings are shown in Table 2. The results show that the carbide coatings provides a 12-46% improvement over bare metal finish. Post-test analysis of the tension plate surfaces indicated that the grits were uniformly embedded into the faying metal surface, which resulted in a strong grip. The abrasive engagement was deep and uniform throughout the metal surface of the tension plate. The grade 4 coating achieved the highest friction rating and was selected for the friction clamp design and prototyping.

Table 2. SECOND SERIES OF SHEAR FRICTION COATING TEST RESULTS

Carbide Coating	Build-up (in)	Peak Load (lbf)	Shear Strength Increase Compare to Bare Metal Surface
None	0	2496	N/A
Grade #1	0.0025	2807	12%
Grade #2	0.006	2808	12%
Grade #3	0.011	3120	25%
Grade #4	0.017	3665	46%

MARK I DESIGN AND PROTOTYPE

The friction clamp allows fiber optic sensors to be mounted on subsea structures for monitoring the structure’s strain and temperature. The Mark I friction clamp has a clamshell design which consists of two corrosion-resistant steel semicircular halves with hinges on one side and bolt flanges on both sides. Fiber optic sensors are bonded at various locations on the outside surfaces of the clamp to detect strain and temperature. Carbide coating is applied on the inside surface of the clamp. Once the clamp is aligned and mounted on the structure that is being monitored, bolts on both sides are tightened to ensure that the clam halves are fastened on the structure with sufficient clamping force to achieve a secure grip with no slippage. The coupling of the clamp to the structure will allow strains on the structure to be transferred to and detected by the sensors on the clamp. The signals are routed through the cabling and sent topside to a data acquisition system for collection and monitoring. A drawing of the Mark I friction clamp design is shown in Figure 4.

In order to evaluate the Mark I design, sub-scale prototypes were built and tested. One friction clamp prototype with a 4-inch diameter and two friction clamp prototypes with an 8-inch diameter were fabricated. A photograph of an 8” friction clamp prototype is shown in Figure 5. The friction clamp prototype clamshells were fabricated by NASA-JSC, and the fiber optic sensors were installed onto the clamshells by ATI. Each friction clamp prototype has 4 axial fiber optic sensors and 1 diagonal fiber optic sensor. The four axial sensors are positioned 90 degrees apart along the circumference of the clamshell. The axial sensors measure the tensile and compressive strains, and the diagonal sensor measures the bias strain.

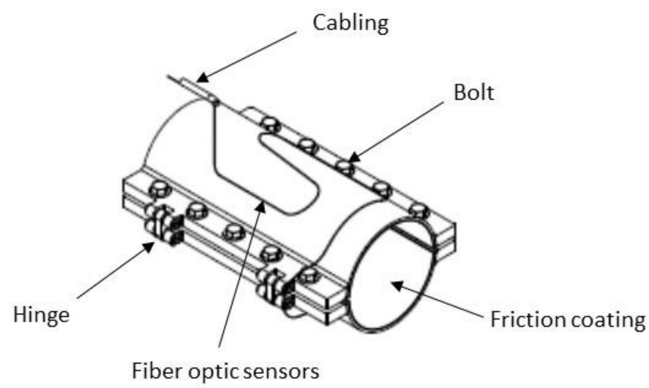

Figure 4. MARK I FRICTION CLAMP DESIGN

Figure 5. 8-INCH FRICTION CLAMP PROTOTYPE

MARK I DESIGN SUB-SCALE PROTOTYPE TESTING

A series of mechanical testing, tension, compression, and bending tests, were conducted at NASA-JSC to evaluate the performance of the friction clamp prototypes. These tests were designed to evaluate the strain measuring capabilities in an assembly configuration that is comparable to a realistic application. The relative accuracy of the strain measurements was used to infer the effectiveness of the prototype attachment mechanism and the reliability of the sensing system.

The friction clamp prototype was installed onto a steel test pipe, which simulate a pipeline structure, to form a test assembly for testing. Two different diameter steel pipes, generally described as 4-inch and 8-inch, were used. They are similar to the API 5L PSL-2 X52 grade pipe. The 4-inch pipe is a NPS 4 Schedule 40 pipe and the 8-inch pipe is a NPS 8 Schedule 10 pipe. The prototypes were installed onto the test pipes with the as-received surface condition in ambient conditions.

One 4” friction clamp and one 8” friction clamp prototype were used for tension/compression testing. The other 8” friction clamp prototype was used for 4-point bending tests. The 4” friction clamp bolts were torqued to 5 ft.-lbf and the 8” friction clamps bolts were torqued to 10 ft.-lbf. Additional torque was applied during tension/compression testing to assess the effect of bolt torque on the clamp’s grip strength and the fiber optic sensor strain measurements. After the clamp installation, conventional resistance strain gauges were also installed on the test pipes to complete the test assemblies. Each test assembly was subjected to various loading scenarios, and the strain measurements from the fiber optic sensors and the resistance strain gauges were recorded and analyzed. The accuracy and resolution of the prototype’s fiber optic sensor system were evaluated by comparing the measurements to the data from the resistance strain gauges. A photograph of a friction clamp test assembly is shown in Figure 6.

Figure 6. TEST ASSEMBLY WITH 4” FRICTION CLAMP PROTOTYPE

The tension and compression tests were performed using a hydraulic load frame with a maximum load capacity of 224,800 lbf (1,000 kN). The test assemblies were tested at two tests speeds, low speed (0.1 in/min) and high speed (0.5 in/min). A 2 Hz data acquisition rate was used to record the fiber-optic sensor data and a 10 Hz data acquisition rate was used to record the resistance strain gauge data. Each test was conducted by loading the test assembly to up to ±110,000 lbf (490 kN) with approximately ±1250 µin/µin strain. The test assembly was held at peak load for up to 180 seconds to observe any measurement abnormality. The test was repeated up to 10 test cycles to observe the repeatability of the measurements. Photographs of the tension/compression test setup are shown in Figure 7. The tension/compression test matrix is shown in Table 3.

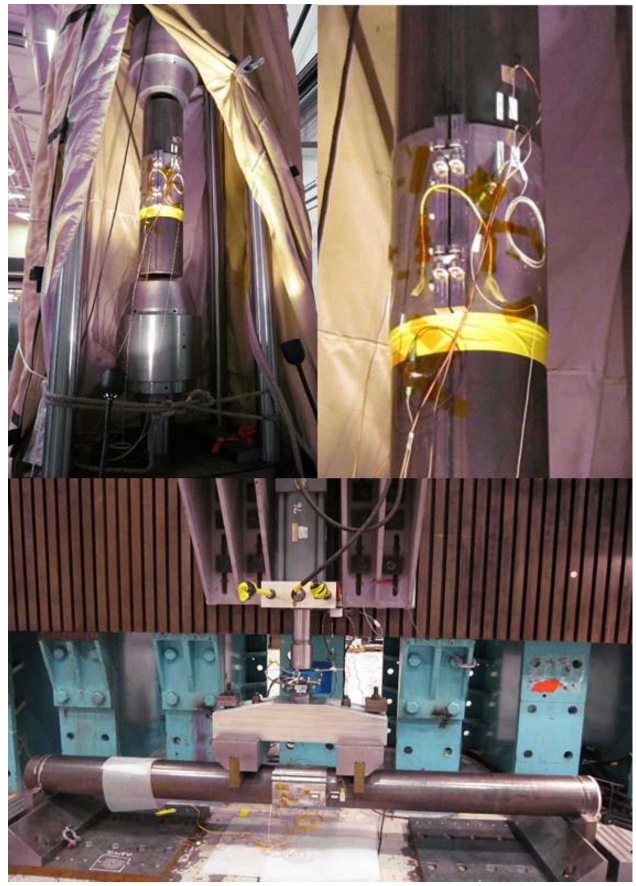

Figure 7. TENSION/COMPRESSION AND BENDING TEST SETUP

Table 3. FRICTION CLAMP TENSION/COMPRESSION TEST MATRIX

Test Number	Test Articles	Test Configuration	Test Speed	Hold Time (seconds)	No. of Repeat / Cycle
TC-1-2	4.5" OD x 0.237" Wall x 36" Length Pipes (Test Article # 1)	Baseline (No Clamp)	Slow	180	10
TC-1-3			High	180	10
TC-1-4			N/A	N/A	N/A
TC-1-6	8.625" OD x 0.148" Wall x 36" Length Pipe (Test Article # 4)		Slow	180	10
TC-1-7			High	180	10
TC-1-11			N/A	N/A	N/A
TC-2-3	4.5" OD x 0.237" Wall x 36" Length Pipes (Test Article # 2)	Friction Clamp with 5 ft.lb Bolt Torque	Slow	180	10
TC-2-4			High	180	10
TC-2-5		Friction Clamp with 7 ft.lb Bolt Torque	Slow	180	3
TC-2-6		Friction Clamp with 10 ft.lb Bolt Torque	Slow	90	5
TC-2-8	8.625" OD x 0.148" Wall x 36" Length Pipe (Test Article #5a)	Friction Clamp with 10 ft.lb Bolt Torque	Slow	90	5
TC-2-9			Slow	90	5
TC-2-10		Friction Clamp with 13 ft.lb Bolt Torque	Slow	90	5
TC-2-11			Slow	90	5
TC-2-12		Friction Clamp with 16 ft.lb Bolt Torque	Slow	90	5
TC-2-13			Slow	90	5

A strongback wall fixture with a hydraulic actuator was used to conduct 4-point bending testing. A set of custom-built 4-point bending support fixtures was used to align and load the test assemblies. A photograph of the 4-point bending test setup is shown in Figure 7. The 4-point bending tests were conducted in both low and high speed of 0.1 in/min (0.25cm/min) and 0.5 in/min (1.27cm/min). Each bending test consists of loading the test assembly to approximately 14,500 lbf (64.5 kN) with up to ±1400 µin/µin strain at the middle of the test assembly. Similar to the tension/compression test procedure, the test assembly was held at peak load for up to 180 seconds to observe any measurement abnormality. Each test was also repeated up to 10 test cycles to observe the repeatability of the measurements. The same data acquisition rates used in the tension/compression tests were also used in the bending test.

Table 4 presents the 4-point bending test matrix. In order to compare the prototype fiber-optic measurements to the benchmark conventional resistance strain gauge measurements, a baseline test assembly was tested and used as benchmark reference. The resistance strain gauges on the baseline test assembly were located the same location as the layout in the friction clamp test assembly. Tests were conducted at different rotational positions ranging from 0 degree to 315 degrees to vary the strain levels experienced by the different strain gauges. A magnetic strip with rotational degree markings was attached to the end of each test assembly to identify the corresponding rotational positioning.

Table 4. FRICTION CLAMP 4-POINT BENDING TEST MATRIX

Test Number	**Test Articles**	**Test Configuration**	**Test Position (Degree)**	**Test Speed**	**Hold Time (seconds)**	**No. of Cycle**
B-1-1	8.625" OD x 0.148" Wall x 120" Length Pipe (Test Article # 7)	Baseline (No Clamp)	0	N/A	N/A	1
B-1-2			**0**	**High**	**180**	**10**
B-1-3			0	High	30	1
B-1-4			0	High	30	1
B-1-5			**30**	**High**	**30**	**10**
B-1-6			**45**	**High**	**30**	**10**
B-1-7			**90**	**High**	**30**	**10**
B-1-8			**180**	**High**	**30**	**10**
B-1-9			**270**	**High**	**30**	**10**
B-1-10			0	Slow	30	5
B-1-11			90	Slow	30	5
B-2-1	8.625" OD x 0.148" Wall x 120" Length Pipe (Test Article # 8)	Friction Clamp (16 ft.lb Bolts Torque)	0	High	30	1
B-2-2			**0**	**High**	**30**	**10**
B-2-3			**0**	**High**	**120**	**3**
B-2-4			**30**	**High**	**30**	**10**
B-2-5			**45**	**High**	**30**	**10**
B-2-6			**90**	**High**	**30**	**10**
B-2-7			**180**	**High**	**30**	**10**
B-2-8			**270**	**High**	**30**	**10**
B-2-9			**135**	**High**	**30**	**10**
B-2-10			**225**	**High**	**30**	**10**
B-2-11			**315**	**High**	**30**	**10**
B-2-12			0	Low	30	5
B-2-13			90	Low	30	5
B-2-14			90	High	30	3.5
B-2-15			90	Slow	30	2

MARK I PROTOTYPE TEST RESULTS AND FINDINGS

The strain measuring capability of the friction clamp prototype was evaluated by comparing the fiber optic sensor strain measurements from the prototypes to the corresponding instrumented strain gauge measurements. The ratio or percentage of the sensor measurement to strain gauge measurement, referred to as performance ratio herein, was calculated to assess the strain sensing performance of the sensor. A sensor with 100% performance ratio will provide the same strain measurement reading as a resistance strain gauge attached directly to the test pipe surface. The friction clamp sensing performance data from all the tension/compression tests are presented in Table 5. The friction clamp sensing performance data from all the 4-point bending tests are presented in Table 6. The maximum tensile strain sensing performance and maximum compressive strain sensing performance were calculated using the peak strain value from the most sensitive axial fiber optic sensor in the test. The minimum tensile strain sensing performance and minimum compressive strain sensing performance were calculated using the peak strain value from the least sensitive axial fiber optic sensor in the test. The red colored values in the table were calculated with the baseline test strain gauge data. The other data were calculated using values from strain gauges located adjacent to the clamp.

Table 5. FRICTION CLAMP FIBER OPTIC SENSOR PERFORMANCE – TENSION/COMPRESSION TESTS

Test Number	Assembly Type / Number	Bolt Torque (ft-lbf)	Number of Test Cycles	Number of Accumulative Test Cycles	Maximum Tensile Strain Sensing Resolution (%)	Maximum Compressive Strain Sensing Resolution (%)
TC-2-1	4" Friction Clamp / #2	5	1	1	N/A	N/A
TC-2-2		5	1	2	N/A	N/A
TC-2-3		5	10	12	3.4	6.7
TC-2-4		5	10	22	3.9	7.4
TC-2-5		7	3	25	9.1	7.9
TC-2-6		10	5	30	13.9	14.9
TC-2-7	8" Friction Clamp / #5a	10	1	1	N/A	N/A
TC-2-8		10	5	6	14.1	43.7
TC-2-9		10	5	11	16.7	46.5
TC-2-10		13	5	16	19.8	50.1
TC-2-11		13	5	21	19.8	51.8
TC-2-12		16	5	26	23.4	52.8
TC-2-13		16	5	31	23.6	53.9

Table 6. FRICTION CLAMP FIBER OPTIC SENSOR PERFORMANCE – 4-POINT BENDING TESTS

Test Number	Rotational Position (Degree)	Number of Test Cycles	Number of Accumulative Test Cycles	Maximum Tensile Strain Sensing Resolution (%)	Maximum Compressive Strain Sensing Resolution (%)
B-2-1	0	1	1	N/A	N/A
B-2-2	0	10	11	20.9	13.4
B-2-3	0	3	14	25.5	18.3
B-2-4	30	10	24	12.2	19.2
B-2-5	45	10	34	19.8	21.5
B-2-6	90	10	44	12	13.9
B-2-7	180	10	54	5.2	14.9
B-2-8	270	10	64	4.8	8
B-2-9	135	10	74	3.4	15.1
B-2-10	225	10	84	14	26.7
B-2-11	315	10	94	8.9	4.7

As shown in Tables 5 and 6, both the 4" and 8" friction clamp prototypes exhibited low sensing performance in both tension/compression test and 4-point bending test. The low performance could be attributed to the indirect coupling of the fiber optic sensors to the test pipe since the fiber optic sensors were located on the exterior surface of the friction clamp. As shown in Figure 8, increasing the bolt torque enhanced the coupling of the clamp and provided a slightly higher sensing performance. However, even at the highest torque level, the highest sensing performance ratio attained was around 50% of the compressive strain. For the tension/compression tests, the 8" friction clamp exhibited much higher sensing performance than the 4" friction clamp. The sensing performance data presented in Figure 8 show that the prototype performed poorly in sensing tensile strain comparing to sensing compressive strain. It is possible that the very slight contraction (necking) and expansion of the test pipe under tension and compression may affected the coupling between the sensors and the pipe. The 8" friction clamp did not work well in the 4 point bending tests and has relatively low sensing performance.

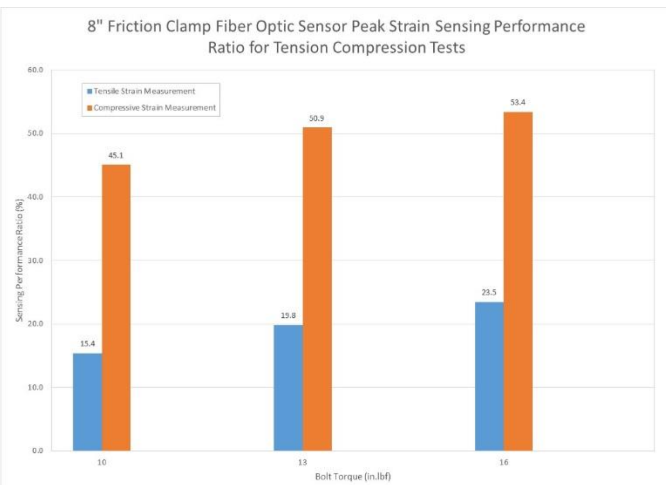

Figure 8. TENSION/COMPRESSION SENSING PERFORMANCE RATIO COMPARSION

A typical strain vs. time plots of the fiber-optic sensor data and the corresponding resistance strain gauge data of tension/compression tests are shown in Figures 9 and 10. The strain measurements from the fiber-optic sensors have a similar responses compare to the resistance strain gauge measurements but the responses are at a much lower magnitude. The fiber optic sensor strain measurements were consistence from the first to the last cycle during the tension/compression tests. However, the measurements were not as consistence in the 4-point bending test. Data dropout and reduction of strain magnitude were observed as the number of test cycle increase. The inconsistences observed during the bending test suggests that the sensor coupling may be compromised.

Figure 9. 8" FRICTION TEST ASSEMBLY FIBER OPTIC SENSOR DATA FOR TENSION/COMPRESSION TEST # TC-2-10

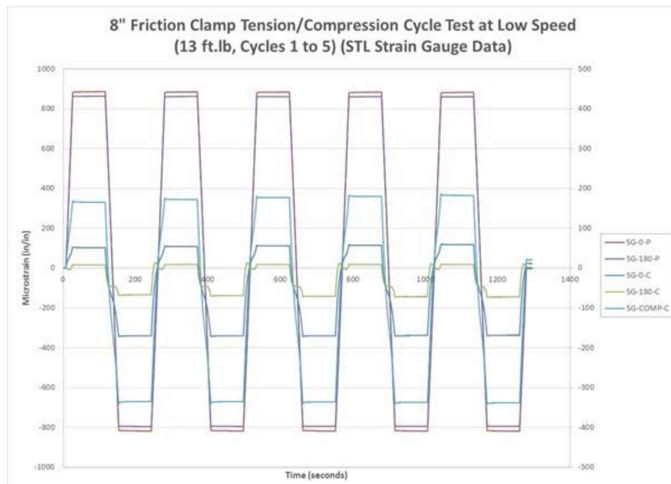

Figure 10. 8" FRICTION TEST ASSEMBLY RESISTANCE STRAIN GAUGE DATA FOR TENSION/COMPRESSION TEST # TC-2-10

The following is a summary of what was learned from the Mark I friction clamp prototype testing:

- The friction coating appears to be quite effective in keeping the friction clamp firmly attached to the pipe surface. No slippage was observed during testing.
- The friction clamp sensing resolution increases with increase bolt torque. However, even at the highest bolt torque evaluated in this study, the highest strain measuring performance ratio is still limited to around 50% of the benchmark value.
- The positioning of the fiber optic sensors on the exterior surface of the friction clamp is not optimal, and it may reduce the sensing performance of the sensors.
- The friction clamp has a significantly lower strain sensing performance when it is under tension during the

tension/compression test. This observation suggests that the necking or contraction of the test pipe during tensile loading may have loosen the sensor coupling to the pipe.

- Sensor coupling to the pipe were significantly degraded during the bending tests when relative large bending deflection was presented. As the number of bending cycles increased, some of the sensor measurements decreased correspondingly.

MARK II DESIGN REFINEMENTS

The findings from the Mark I prototype testing demonstrated that there are several weaknesses in the design that need to be addressed in order to improve its performance to be a viable product. There are several technical challenges, but they can be overcame with redesign and refinement. The following is a list of design changes and refinements incorporated into the Mark II design to address the Mark I design shortcomings.

- Redesign of the friction clamp shell and fiber-optic sensor attachment method to provide a more secure and direct coupling to the structure.
- The redesign clamp shell has a shorter and more compliance profile that will provide a more uniform surface contacts. The redesign clamp cell geometry is also less susceptible to surfaces decoupling due to large bending deflection.
- Incorporate a self-locking mechanism that provides constant clamp force to counteract the contraction of the structure under tension loading.
- Incorporate additional sensors to provide redundancy and to improve overall system reliability.

MARK II DESIGN PRELIMINAEY EVALUATION

A full size Mark II prototype was built by ATI and tested. A photograph of a compression test setup is shown in Figure 11. At the time of this writing, the data from the Mark II prototype testing had not been fully analyzed yet. However, preliminary results indicated that the fiber-optic sensor measurements were tracking well with the reference strain gauge measurements. There are also less deviation between the tension and compression measurements, which suggests that the new design was maintaining a high level of coupling during the tension tests. Preliminary strain data from the Mark II prototype tension/compression tests are shown in Figure 12.

The Mark II design appears to have resolved some of the technical shortcoming of the Mark I design. The continued development of the friction-based post-installable fiber-optic sensor system could yet a valuable health monitoring system that could significantly enhances the operational safety of offshore oil and gas operations.

Figure 11. MARK II PROTOTYPE COMPRESSION TEST SETUP

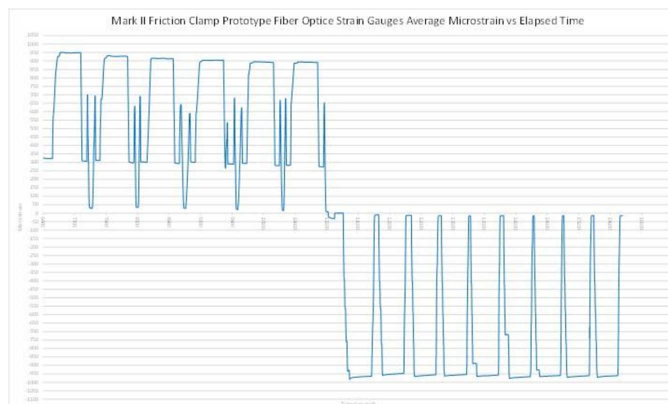

Figure 12. MARK II PROTOTYPE TENSION/COMPRESSION TEST PRELIMINARY STRAIN DATA

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